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Reconstruction of Binocular Depth across Continuous Surfaces

This technical report consists of two publications. The first will appear in the *Journal of Experimental Psychology: Human Perception and Performance* in 1989. This article examines the perception of depth in random dot surface versus volume stimuli, and shows that depth associated with a continuous surface is subject to reconstruction artifacts, where equivalent random-dot volume stimuli are used as a control. The second article has been submitted for publication. This article explores the analogy between the reconstruction of stereoscopic depth and the reconstruction of brightness. The analogy holds for a number of classical simultaneous contrast effects. Dissimilarities are found, however, in terms of the lateral inhibition effects traditionally attributed to underlying spatial-differention operators.

BINOCULAR DEPTH FROM SURFACES VS. VOLUMES

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Running head: Binocular depth

Abstract. The depth of a pair of binocular targets embedded in surfaces is shown to be influenced by the apparent depth and slant of the underlying surfaces. Random dot stereograms were generated with a sawtooth (triangle-wave) disparity profile, which corresponded to a set of slanted planar surfaces separated by sharp depth discontinuities. The stimuli were chosen to capitalize on the known difficulty in perceiving slanted planes in binocular depth. Two targets were embedded in these surfaces, either on adjacent surfaces separated by one depth edge or at a greater separation with three intervening depth discontinuities. The targets were also embedded in a random volume of points as a control context. The apparent depth of the targets was influenced by the context, with the surface stimuli misperceived as having a stairstep profile in depth. The effect suggests a distinction between the depth processing of isolated points within a volume versus points associated with the interiors of continuous surfaces.

Introduction

For distances measured radially from an observer, the *depth* associated with a given location is the difference in distance between that location and a given reference location. Depth, which is generally small compared to the overall reference distance, is often used to describe incremental distance variations, such as surface relief. *Apparent depth* is presumably the direct perceptual counterpart to this geometric quantity, so that the apparent three-dimensionality of viewed surfaces is usually expected to correspond to the determination of apparent depth for points across the given surface. There is, in principle, a direct geometric relationship between depth and binocular disparity, where the point of convergence of the two eyes provides a natural reference distance (see formulations in Foley, 1980; Mayhew, 1982). At least in the near field, depth has been shown to be directly related to disparity and convergence (Richards & Miller, 1969; Ritter, 1977, 1979; Foley, 1980; Morrison & Whiteside, 1984). The visual system partially compensates for the dependency of depth on the square of the distance to the point of convergence (Ono & Comerford, 1977; Wallach, Gillam & Cardillo, 1979). Foley (1980) has shown that systematic errors in binocular depth can be attributed to errors in the estimation of the apparent reference distance based on an extraretinal convergence signal. Vertical disparities or eye movements have also been proposed as contributing to determining the geometric parameters of the binocular system necessary for recovering depth (Longuet-Higgins, 1982a, b; Mayhew, 1982; Prazdny, 1983). It should be noted that while binocular disparity is often described in terms of absolute retinal positions, there is evidence that the effective binocular disparity is determined by differences between the two half-images, as suggested by our ability to maintain stable fusion despite retinal motion (Steinman & Collewijn, 1980; Steinman, Levinson, Collewijn, & van der Steen, 1985; Lappin, 1985).

It has been widely presumed that binocular depth across continuous surfaces is a straightforward extension of that associated with discrete binocular features. A continuous surface would present a rather dense sampling of binocular features, each contributing to the impression of depth at the corresponding surface location, probably on the basis of local disparity differences or contrast (Gogel, 1956, 1972; Gulick & Lawson, 1976). The importance of disparity contrast, and not absolute disparity, in determining apparent depth was first suggested by certain "depth contrast" effects (Werner, 1938, 1942; Pastore, 1964; Pastore & Terwilliger, 1966). A simple example of depth contrast is that of a central line at 0° disparity surrounded by flanking lines or dots that have disparities consistent with lying on a slanted plane: the central line will appear to slant away from the (apparently unslanted) frame. Depth contrast effects have been attributed primarily to the process of binocular fusion, e.g. cyclotorsion or shifts in effective correspondence (Ogle, 1946; Nelson, 1977) perhaps with the apparent frontoparallel, or zero-disparity, plane influenced by monocular cues (Harker, 1962).

While disparity contrast seems necessary for the perception of apparent depth, recent observations suggest that it is not sufficient. Specifically, coplanar arrangements of binocular features, corresponding to slanted planes, have been found relatively ineffective in inducing apparent slant. Gillam, Flagg, and Finlay (1984) found that the slant of a plane is perceived much more rapidly when bounded by disparity discontinuities, and that, in their absence, depth develops with a slow time course similar to that reported in "aniseikonia" experiments (Ames, 1946). Mitchison and Westheimer (1984) also found that depth derives less effectively when the disparity features correspond to a coplanar arrangement, i.e. lying on a slanted plane. They found that the threshold for detection of apparent depth is elevated when adjacent binocular features are coplanar, and that the slant is particularly difficult to discern for certain arrangements,

particularly those that monocularly suggest an unslanted configuration, such as a square (Werner, 1937; Westheimer, 1979; McKee, 1983). The dominance of the monocular interpretation over constant disparity gradients was shown recently (Stevens & Brookes, 1988) for a variety of stereograms in which the distribution of binocular disparities corresponded to a slanted plane whose orientation was inconsistent with the monocular interpretation (e.g. as suggested by linear perspective). Given a sufficiently compelling monocular configuration, even very large contradictory disparity gradients are ineffective, provided they correspond to coplanar binocular features, and are presented in the absence of boundary disparity contrast.

The observations that binocular depth is dependent on the presence of disparity contrast and that depth is least reliably recovered from constant disparity gradients suggests an analogy between depth from disparity contrast and brightness from luminance contrast. Central to the analogy is that binocular depth, like brightness, appears to be reconstructed across continuous regions bounded by contrast edges, as demonstrated by the depth analogue of the Craik-O'Brien-Cornsweet (Anstis, Howard & Rogers, 1978). Other brightness analogues can be demonstrated, e.g. a constant disparity gradient induces a complementary slant in a ring of constant disparity (Stevens & Brookes, 1987; Stevens, Note 1) — an effect likely related to depth induction first observed by Werner (1938). See (Brookes & Stevens, 1988) for discussion of the limits of this analogy.

Several explanations have been offered for the observed insensitivity to low spatial frequency variations in disparity, including spatial lateral inhibition (Anstis *et al.*, 1978; Tyler, 1983) and local processes that align retinal images prior to binocular fusion (Anderson & Van Essen, 1987). But while some low spatial frequency depth information is seemingly lost at an early stage of binocular processing, the various depth contrast

effects just mentioned show that at least some of that information is subsequently reconstructed. But other than demonstrating the existence of binocular depth reconstruction, little more is known about it.

Mitchison and Westheimer (1984) characterize depth as being derived from differences in local disparity contrast, observing, for example, that lines that have the same disparity difference between themselves and their neighbors appear at equal depths. This accounts for a variety of phenomena involving coplanar binocular arrangements which exhibit little apparent depth, but their explanation seems to us more closely tied to the local detection of surface curvature or discontinuity features based on disparity than on the overall reconstruction of depth. More generally, our experience with similar stimuli has been that features embedded in continuous surfaces assume the apparent depth of the immediately underlying surface, which might consequently cause the features to appear at different depths, on the basis of, e.g., monocular cues (Stevens & Brookes, 1988). We examined here whether this tendency also holds for purely binocular stimuli.

Experiment

The approach was to use two types of random dot stereogram (RDS) stimuli: one in which the dots are given systematically varying binocular disparities that correspond to a triangle-wave surface, i.e. a series of linear ramps separated by sharp disparity discontinuities (figure 1a); in the second type of RDS stimulus, which served as a control, the points were distributed randomly in disparity so that they appeared to lie scattered throughout a volume of space (figure 1b). The stimuli were presented with no visible disparity contrast with the margins of the display; the only contrast was within the

RDS, either among the dots of the volume stimuli or, in the case of the triangle-wave stimuli, across the vertical margins between adjacent slanted planes. Of particular importance to this experiment is the fact that the impression of overall depth from the triangle-wave disparity profile is incorrect. Rather than appearing as a series of slanted planes at a common mean distance from the observer, their slant in depth is underestimated, so that the sharp disparity discontinuities between planes induce an erroneous overall increase in depth across the pattern. The RDS is seen in depth immediately as an arrangement of slightly slanted planes, whose apparent overall depth variation is intermediate between a triangle-wave and a staircase profile. The magnitude of the staircase effect is at least as large as that observed in the depth analogue to the Craik-O'Brien-Cornsweet effect (Anstis *et al.* 1978). Given these two stimuli, subjects were asked to compare the relative depth of two embedded target points that could be readily discerned from the other points of the RDS.

The intention of this experiment is to demonstrate a dependence of binocular depth on the presence of continuous surfaces. The stimuli are intended to be purely binocular, as afforded by random dot stereograms containing no monocular surface features. It is conceivable that the fused stereogram contains residual monocular depth or slant cues that might influence the results. For example, dot density was uniform across the stereograms, and the individual dots were all the same size (slightly less than one arc minute), both of which indicating a stimulus equidistant from the observer, contrary to the binocular interpretation. These influences, if measureable, would apply equally to all RDS stimuli, and presumably serve to reduce the impression of varying depth. The more important effect pursued here is the influence of surfaces on the apparent depth of embedded target points.

< figure 1 (a and b) about here >

Method

Apparatus: The RDS stimuli were generated by a Symbolics 3675 Lisp Machine and displayed on a Wheatstone-style stereoscope consisting of a pair of optically-flat front-surfaced mirrors and Tektronix 634 monochrome displays. The monitors were 94 cm from the observer, as measured along the optic axis from eye to screen, and viewed with a convergence angle consistent with the observation distance. The stimulus stereogram subtended approximately 7° and consisted of luminous points against a dark background; the stereoscope was viewed in darkness.

Stimuli: For the RDS triangle-wave surface stimuli consisted of 2000 points whose disparities corresponded to four slanted planes each subtending 1.8° horizontally by 5.8° vertically. Disparity varied linearly across each slanted plane and discontinuously across the vertical margins between adjacent planes. The overall disparity range was -1.53′ to 6.13′, well within Panum's fusional limit. The disparity gradient across each plane corresponded to one of two slants in depth, varying either 4.6′ or 6.1′ over the 1.8° width of the plane (see disparity profile in figure 2).

< figure 2 about here >

Superimposed onto the RDS were two target points, each subtending 3′ so as to be distinguishable from the RDS points, with binocular disparities that matched the triangle-wave profile at its projected location so that each target appeared to lie flush with the surrounding RDS surface. The two targets were positioned on the horizontal meridian to the left and right of the vertical meridian. The targets were either embedded in the central two planes (separated by 2° and one depth edge) or the outer two planes (separated by 6° and three intervening depth edges). We will refer to these as the near- and far-separation conditions. Figure 1 shows the two targets in the far-separation

condition. For each of the two separations, the targets could appear in slightly different lateral positions on their corresponding slanted planes, so that four different relative disparities would result, specifically $\pm 1.5'$ and $\pm 3.1'$. Geometrically, a positive disparity difference corresponded to the left target nearer than the right while a negative disparity difference corresponded to the right target nearer. The smaller disparity difference ($\pm 1.5'$) was chosen empirically to be a challenging relative depth task for targets separated by 6° amidst the other "distractor" points of the RDS. Altogether 6 combinations of binocular disparity were provided: the four combinations just described plus two conditions where the two targets had equal disparity but different locations on their respective surfaces. Note that since the two targets appeared on ramps of differing disparity gradient, the relative depth judgement could not be deduced merely from their relative placement on the underlying planes. The mean disparities of the ramps were chosen in order to accommodate the range of relative target disparities.

A second experimental series was performed with the two targets embedded in random dot volume stimuli (figure 1b). In this case the same 2000 dots were given random disparities within the same overall disparity range of $-1.53'$ to $6.13'$ used before. The dots that comprised the volume stimuli were fused readily and immediately appeared to define a volume of distinct points that were scattered in depth. The same six combinations of target location were used in these volume stimuli in conjunction with the two disparity senses (normal and reversed). Unlike the triangle-wave surface stimuli, where the targets appeared to lie on surfaces in depth, the targets in this series appeared to float in space amidst a random field of other 3D points.

Procedure: Five experienced subjects participated in the experiment, four of whom were naive to the nature of the experiment; all had good stereo vision. In each trial the

stimulus RDS was presented for 1000 msec without the two targets, followed by an additional 750 msec during which the target points were superimposed on the RDS. The subjects were told that they would see a pair of target points embedded in either a configuration of surfaces or a volume of points, and that they were to decide quickly but reliably which of the two targets appeared closer to the subject. The subject indicated the left or the right target by pressing the corresponding button on a mouse. The subjects were not given feedback about the accuracy of their judgments.

The experiment consisted of two series of trials, the triangle-wave surface stimuli (figure 1a) followed by the random volume stimuli (figure 1b). Each series consisted of 120 trials presented in random order: 5 repetitions of each of 12 distinct stimulus conditions, each presented for two choices of RDS disparity sense (normal and reversed, which served to reverse the direction in which depth increased in the apparent staircase). Note that the disparity reversal was for the entire stereogram, including the targets. The 12 conditions were comprised of 6 choices of position for the two targets and two target separations (near and far). Subjects were given learning trials without feedback until they indicated that they were comfortable with the task.

Results and Discussion

For the volume stimuli, the relative depth of the two targets was judged reliably for both the near (2°) and far (6°) separations. The far-separation case, not surprisingly, produced slightly more errors, particularly when the targets differed by only $\pm 1.5'$ in disparity (17% errors of the corresponding trials). In comparison, when the targets differed by $\pm 3.1'$ in disparity, their relative depth was judged accurately (1% error) despite the large separation and the many intervening depth points.

The performance was quite different when the target points were embedded in the triangle-wave stimulus. An ANOVA was performed to test the main effects of *i)* the surface versus volume background, *ii)* target separation, and *iii)* disparity difference. The presence of the surface was found to be significant ($F(1,4) = 22.84$, $p < .05$). For the far-separation case, subjects had a strong tendency to make relative depth judgments consistent with the targets lying on separate planes in depth arranged as a staircase (rather than as a triangle-wave profile of slanted planes), despite the contradictory depth ordering implied by their disparities. For targets that were separated by only 2° (and lying on adjacent planes) the depth judgments were more in accordance with disparity, but still were judged contrary to disparity in 22% of the trials, in comparison to 5% for the volume stimuli. This corresponds to the subjective impression that the illusory staircase is relatively weak over adjacent step discontinuities, and is most apparent when judging the relative depth of two points separated by several step edges. The cases most consistent with the illusory staircase involved targets separated by 6° (three intervening step discontinuities) and 1.5′ in disparity: the targets were seen in depth according to the apparent staircase and contrary to their disparity difference in 90% of the trials. Even for targets with a disparity difference of 3.1′, their relative depth was contrary to disparity in 66% of the trials, compared to 1% in the corresponding volume stimuli.

In table 1 the data are collapsed across disparity reversals and presented in a manner that emphasizes the degree to which the responses were consistent with the staircase depth interpretation. As a basis for comparison, the first row shows how relative depth would be judged if based exclusively on binocular disparity. The data are presented with the convention that the apparent staircase increased in depth from left to right, so that a positive disparity difference would be consistent with the staircase. Note that the two conditions where the targets had 0° disparity difference are presented

together in the center column. For the volume stimuli there would be no expected bias (hence the .5 prediction) but for the surface stimuli we expected a bias if the targets were seen as lying at different depths on the apparent staircase. Note that the data for surface stimuli show an orderly bias towards the staircase interpretation, particularly for the far-separation case.

< table 1 about here >

It has been demonstrated by many studies that depth can be derived reliably from disparity contrast for spatially isolated targets. The targets in these stimuli were not isolated, however. It has been shown that binocular points in close proximity, separated by less than about 6-8′, exhibit depth averaging and spatial attraction and repulsion effects (Mitchison & McKee, 1985; Westheimer, 1986; Westheimer & Levi, 1987). In our experiment the dot density was such that several background points could be expected to lie within approximately 6′ of each target. It is therefore conceivable that the relative depth of the targets was perturbed by adjacent RDS points, which contributed to the observed error rates. These perturbations, of course, would not have systematically influenced the target depths in the triangle-wave stimuli.

Probably more relevant is a second type of spatial interaction, which, as discussed earlier, tends to reduce apparent depth among coplanar binocular features. We expect that binocular depth is reconstructed across regions of continuous disparity change on the basis of the boundary conditions, such as the sharp disparity discontinuities between adjacent planes in the triangle-wave stimuli. Since we are relatively insensitive to the disparity gradient within the individual slanted planes, the reconstruction process erroneously accumulates an overall depth increase across subsequent planes, giving the impression of a staircase in depth. Since the targets were perceived as lying on the surfaces,

their apparent depths were consequently subject to errors of depth reconstruction.

Conclusions

The relative depth of a pair of isolated targets separated by a visual angle of several degrees and by several minutes of disparity can be readily determined from their binocular disparities. In the present experiment this was demonstrated by the volume condition in which the two targets were embedded in a volume of distractor points. In the surface condition, the positions of the distractor points were held constant, but their disparities were distributed systematically rather than randomly in depth. Thus, the only difference between stimuli in the two conditions was in the disparity distribution of the distractor points. When the distractor points defined continuous surfaces, the relative depths of the embedded targets were no longer determined solely by their relative disparities. Rather, the target points acquired the depth of the embedding surfaces, and thus became subject to reconstructive errors in the perception of the surfaces.

The surface condition stimuli were designed to introduce an illusory impression of a staircase in depth, by capitalizing on the relatively greater percieved depth produced by sharp disparity edges than by continuous ramps of similar overall disparity contrast. This effect allowed us to demonstrate that depth judgements for target points on continuous surfaces are mediated by processes that access the reconstructed depth of the underlying surfaces, rather than being determined by their true disparity difference.

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Table 1.

Fraction of Depth Responses as a Function of Disparity Difference

	Disparity difference				
	-3.1	-1.5	0.0;0.0	1.5	3.1
Predicted fraction	0.0	0.0	.50;.50	1.0	1.0
Volume					
Near-separation	.02	.08	.36;.56	.96	.98
Far-separation	.02	.14	.40;.42	.80	1.0
Surface					
Near-separation	.10	.34	.88;.64	.98	.98
Far-separation	.66	.90	.96;.90	.98	.98

Note. Depth responses as a function of the difference in disparity of the two target points, for combinations of target separation and surface versus volume. The disparity differences are indicated in arc minutes. The central column shows the two conditions where the targets had equal disparity. The first row shows the fraction of depth judgements predicted purely on the basis of their relative binocular disparities, hence 0.5 for the two cases of equal disparity. Below are the fraction of judgments consistent with the illusory staircase in depth seen in the sawtooth surface stimuli, where 1.0 would indicate all depth judgments corresponding with the targets lying on separate levels of the

apparent staircase.

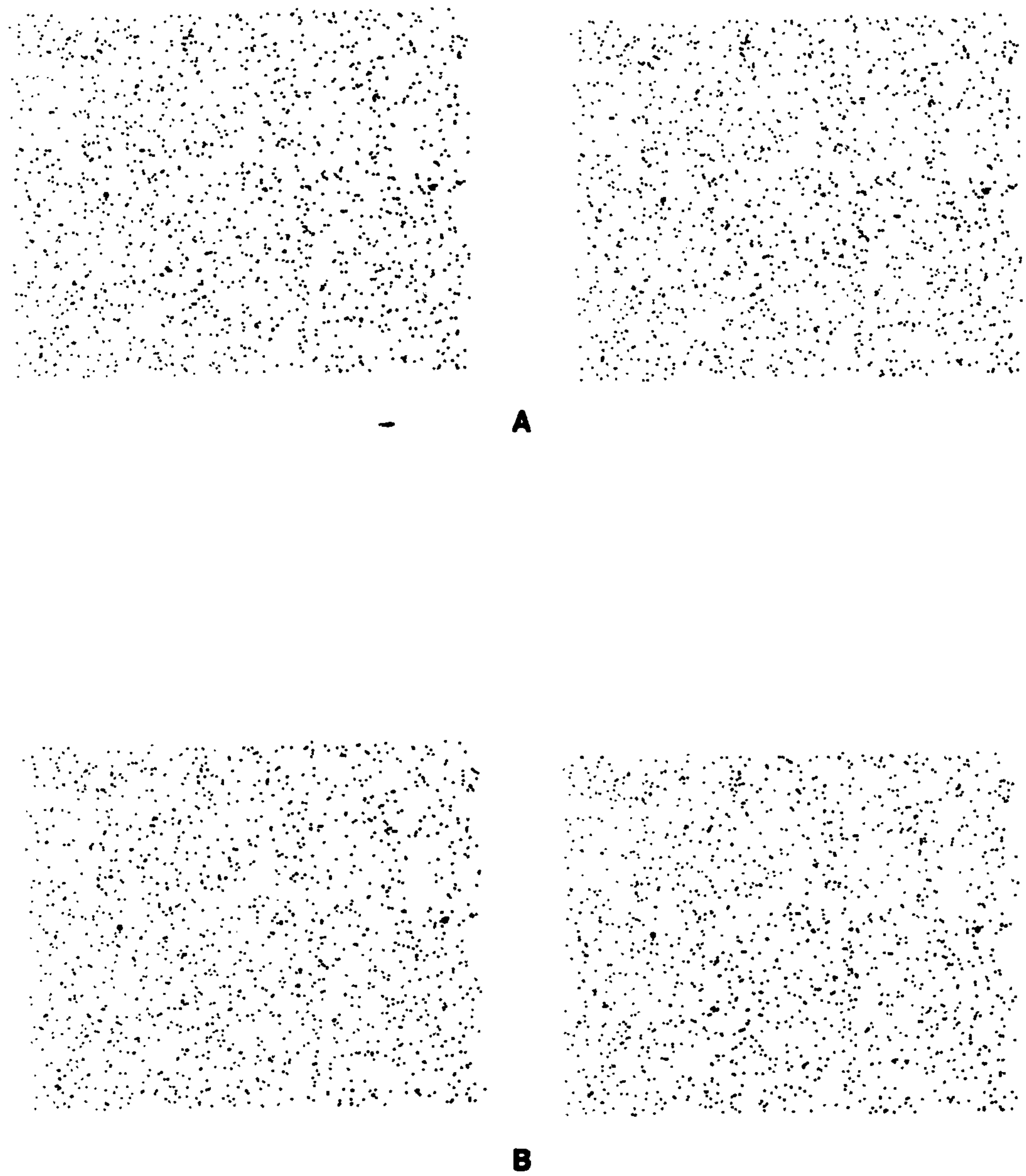

Figure 1. RDS stimuli similar to those used in the experiment. In *a)* the disparities correspond to a triangle-wave surface, but seen as having an overall staircase variation in depth. In *b)* the disparities are distributed randomly, giving the appearance of a volume of points.

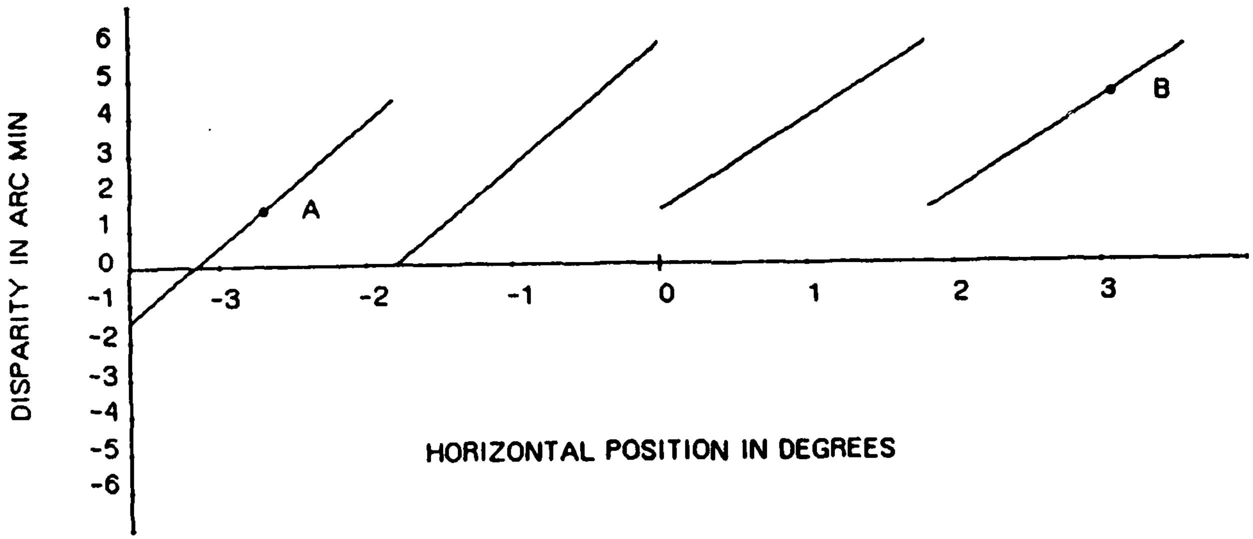

Figure 2. Disparity profile of the triangle-wave surface shown in figure 1a. A binocular target at location A tends to be seen as nearer than a target at location B, despite their relative disparities. Crossed disparities are negative in this figure.

THE ANALOGY BETWEEN STEREO DEPTH AND BRIGHTNESS[1]

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Short title: Stereo Depth and Brightness

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Abstract. Apparent depth in stereograms exhibits various simultaneous-contrast and induction effects analogous to those reported in the luminance domain. This behavior suggests that stereo depth, like brightness, is reconstructed *i.e.* recovered from higher-order spatial derivatives or differences of the original signal. We examine the extent to which depth is analogous to brightness, and find similarities in terms of contrast effects but dissimilarities in terms of the lateral inhibition effects traditionally attributed to underlying spatial-differentiation operators.

1 Introduction

Stereo disparity contrast can induce "depth contrast" in a manner analogous to various well-known brightness contrast effects. A classic brightness contrast demonstration is shown in figure 1a, a variant of Koffka's ring (Koffka 1935). A uniform-luminance circle is embedded in a constant luminance gradient background. The variable contrast between the ring and its immediate background induces variable apparent brightness around the circle. Analogously, the stereogram in figure 1b consists of a uniform-disparity circle embedded in a constant disparity gradient background. The circle appears slanted in depth in the direction opposite that of the background gradient. Just as the brightness in figure 1a is dependent on luminance contrast more than absolute luminance, so is apparent depth in figure 1b dependent more on disparity contrast than on absolute disparity.

Depth contrast effects were first observed in simple stereograms in which a figure at zero disparity appears to slant in depth as a consequence of its surrounding context (Werner 1938, 1942; Pastore 1964; Pastore and Terwilliger 1966). Ogle (1946) suggested that during the fusion process, in attempting to bring the context to zero disparity, cyclotorsion induces opposite disparity in the figure. Nelson (1977) later provided various experiments that ruled out cyclotorsion as the sole explanation, and furthered Werner's (1938) proposal that disparity *contrast* is responsible for the induction of apparent depth. In a manner

analogous to the relationship between brightness and luminance contrast, the apparent depth in certain stereograms seems more reliably related to disparity contrast than to absolute disparities.

The analogy between depth and brightness was made explicit in discussion of a stereoscopic counterpart of the Craik-O'Brien-Cornsweet illusion (Anstis, Howard and Rogers 1978; Rogers and Graham 1983). In the luminance version of this illusion, two fields of equal luminance meet at a border whose profile is shaped like a double spur. The impression is of two homogeneous regions differing in brightness separated by a sharp step edge. In the depth version, one of the fields is seen as closer. The illusion demonstrates that depth information is extrapolated over extended regions bounded by sharp disparity edges, much like the extrapolation of brightness information away from intensity edges.

< figure 1 (a and b) about here >

Brightness perception has been treated mathematically as two-dimensional integration of a derivative-like retinal signal (Arend 1973; Blake 1985; Schiffman and Crovitz 1972; Arend and Goldstein 1987). Brightness artifacts can be regarded as failures to achieve an accurate reconstruction of the incident signal, in part due to information lost by the initial derivative-like measurements (e.g. from thresholding).

Several brightness phenomena can be neatly described in terms of an empirically-measured spatial modulation transfer function (MTF) (Cornsweet 1970). The retinal receptive field presumed to be largely responsible for the overall shape of the MTF is traditionally modelled as a difference of Gaussians (DOG), (Rodiek and Stone 1965; Enroth-Cugell and Robson 1966). The resemblance of this circular-symmetric operator to the Laplacian of a Gaussian has been noted (Marr and Hildreth 1980), although the actual ratio of space constants (between excitatory and inhibitory Gaussians) in retinal DOGs is far too great to constitute a quantitative approximation to the Laplacian of a Gaussian

(Robson 1983). Nonetheless, center-surround antagonism provides the qualitative effect of Laplacian filtering, and the component Gaussian receptive fields of the DOG achieves the effect of low-pass filtering, relative to the size of the operator. Lateral inhibition thus underlies both the insensitivity to low spatial frequency luminance variations and for the relative sharpening of sensitivity to luminance discontinuities (both of which are demonstrated by the Craik-O'Brien-Cornsweet illusion). Lateral inhibition has also been invoked to explain other instances of diminished sensitivity to low spatial frequencies, e.g. of line spacing, line length, and velocity (MacKay 1973; Loomis and Nakayama 1973; Crovitz 1976).

Stereo depth likewise exhibits an effective spatial MTF. Sensitivity to sinusoidal spatial modulations of stereo disparity is limited to about a maximum of 5 cycles/deg, with peak sensitivity at about 1 cycle/deg, and gradually diminishing sensitivity with decreasing spatial frequencies (Tyler 1973, 1975). The maximum sensitivity and the high-frequency limits are consistent with independent evidence that continuous disparity distributions are spatially integrated within areas of approximately 0.5 deg in diameter (Tyler and Julesz 1980). The gradual low frequency fall-off has been attributed to spatial lateral inhibition, e.g. by center-surround antagonism (Anstis et al. 1978; Schumer and Ganz 1979; Tyler 1983; Schumer and Julesz 1984). It should be noted that two types of lateral inhibition can be expected in disparity processing: *i)* spatial interactions, with summation or pooling of disparity signals within subfields and (center-surround) antagonism across spatially-separated subfields, and *ii)* inhibition *across* disparity-tuned channels at a common location (Richards 1972; Tyler and Foley 1974; Nelson 1975; Julesz 1978; Marr and Poggio 1980; Westheimer 1986; cf Prazdny 1985). The high spatial frequency limit would be evidence for spatial pooling or averaging of the disparity of closely-spaced features. Recently, Westheimer and Levi (1987) showed that, within about 4-6 arc min, binocular points show attraction in depth, and beyond that distance, repulsion in depth.

Do the substantial similarities between depth contrast and brightness contrast phenomena reflect similar processing strategies? We suggest that the observed similarities arise primarily from the fact that binocular depth and brightness are both reconstructed from (disparity or luminance) contrast, but that the analogy is limited because the corresponding contrast features are detected by fundamentally different strategies. The analogy is further limited by some evidence that the reconstruction strategies themselves also differ.

The discussion that follows gives instances where the analogy holds dramatically and obviously, and others where the analogy seems to fail. Where we report it fails, we are summarizing our experience over a variety of stimuli using several experienced stereo observers. In the cases where the analogy holds, the effect in stereo depth is similar in strength to the traditional brightness effect. On the other hand, we were unable to find a stereo counterpart for several other brightness effects. The breakdown of the analogy in these instances is regarded as significant in light of the strength and robustness of the original brightness effects.

2 Brightness and Depth Effects Associated with Reconstruction

The Craik-O'Brien-Cornsweet illusion in stereo depth is compelling evidence that stereo depth derives from a process that reconstructs surfaces indirectly from boundary contrast. There are other demonstrations that depth derives from relative disparities, i.e. disparity differences within the binocular configuration, as opposed to absolute retinal disparities (Steinman & Collewijn 1980; Lappin, 1985). The stereo analogue of the Craik-O'Brien-Cornsweet effect further shows that stereo depth is subject to errors in integrating overall depth differences from subthreshold disparity variations. The difference in apparent distance from the observer to the left and right extremes of the pattern reflects a failure to incorporate the very low spatial frequency changes into the accumulated depth variation over the pattern. Note that judging which side appears closer requires comparing apparent

radial distances. It is therefore remarkable that even with free eye movements observers cannot perform the task by directly comparing the disparities of the two regions. Clearly the distribution of the surfaces in space is dominated by a (disparity) contrast-based reconstruction, seemingly in close analogy to the reconstruction of brightness in the original illusion.

The demonstration of "simultaneous disparity contrast" in figure 1 further shows that the perception of depth differences and of slant derives from local disparity contrast, e.g. across disparity discontinuities. Apparent slant across a continuous surface is no more reliably related to the local disparity gradient than is absolute depth to absolute disparity. The effect is thus closely analogous to brightness. One can readily generate further depth induction counterparts to other brightness induction demonstrations. For instance, just as two adjacent bars of the same luminance have different apparent brightnesses when presented against a luminance ramp background, adjacent lines of equal disparity appear at different depths when presented with a uniform disparity gradient background (Mitchison and Westheimer 1984). These effects are not at all subtle: the ring in figure 1b appears dramatically slanted despite its uniform binocular disparity.

The local nature of the depth induction effect can be demonstrated by means of a nonlinear background gradient, as shown in figure 2. In the luminance version (figure 2a) the constant-luminance ring is embedded in a Gaussian-shaped luminance profile. The brightness of the ring likewise varies with opposite sign to the background gradient. In the corresponding depth version the constant-disparity ring is embedded in a Gaussian-shaped ridge in depth (figure 2b). The ring appears to curve in depth with induced curvature opposite to that of the background ridge. The curvature in depth induced in the constant-disparity ring is consistent with depth being dominated by the local disparity contrast, as is brightness by local luminance contrast.

< figure 2 (a and b) about here >

Simultaneous *brightness* contrast is also seen when two squares of equal luminance are embedded in backgrounds of differing luminance. The square in the lighter background appears darker than the square in the darker background. Does it have a counterpart in stereo depth? The corresponding stereogram (figure 3) consists of two squares of equal binocular disparity embedded in regions of opposite disparity sign. For the analogy to hold, the square embedded in the negative-disparity background should appear farther than that embedded in the positive-disparity background. But we find no corresponding depth difference in this configuration: the squares appear equidistant from the observer. The brightness-contrast effect is often attributed to a logarithmic transformation of incident luminance (Cornsweet 1970): the compressive transformation results in differing effective contrasts prior to lightness reconstruction, and consequently differing apparent brightnesses. But no corresponding compressive transformation is found or expected for disparity.(see Foley and Richards 1971; Foley 1980).

< figure 3 about here >

Another simultaneous contrast effect is the apparent variation in brightness within a region of constant luminance induced by the contrast across its borders with adjacent regions. Figure 4a, for example, shows a staircase pattern of rectangles of progressively higher luminance from left to right. Each rectangle appears lighter near the left margin and darker toward the right, an effect explicable quite directly in terms of the spatial MTF (Cornsweet 1970).

Figure 4 presents the analogous stereo stimulus: a staircase disparity profile. The apparent depth profile is roughly analogous to the brightness version: the individual rectangles, despite their uniform disparity, appear slanted in depth. Although the depth increment across each sharp discontinuity is perceived rather accurately, apparent depth does not accumulate correctly over the staircase. As a result, the overall arrangement resembles a set of louvers, with the left side of each slanted rectangle appearing farther that the right.

< figure 4 about here >

The misperception of depth in the disparity staircase is predicted by the stereo MTF, much as the corresponding contrast sensitivity MTF predicts apparent brightness for the luminance staircase. But more is involved than is captured merely by a bandpass-filter model. A repeating triangle-wave disparity pattern, with constant mean disparity over the pattern, would be predicted on the basis of the MTF to be seen in depth veridically, but in fact is misperceived as a staircase depth profile (Brookes and Stevens 1989). Apparent depth increases across the pattern in a manner analogous to the accumulation of brightness reported for triangle-wave luminance profiles sequences of Craik-O'Brien-Cornsweet edges (Arend, Buehler and Lockhead, 1971; Arend 1973; but see Coren, 1983). Exceptions to the analogy concern the failure to observe perturbations to the apparent depth profile in the vicinity of disparity discontinuities, the analogues of luminance effects traditionally attributed to lateral inhibition. We discuss this aspect of the analogy next.

3 Effects Associated with Lateral Inhibition

Several brightness phenomena appear to directly implicate neural mechanisms that might underlie aspects of the effective spatial MTF of the visual system. The first such mechanisms in the visual pathway are the retinal ganglion cells which, as mentioned, perform (spatiotemporal) derivative-like filtering by spatial lateral inhibition.

Mach bands are perhaps the most compelling illustration of lateral inhibition. The effect is an apparent creasing of the brightness profile where the corresponding luminance profile exhibits a sharp discontinuity in second derivative. For example, dark and light lines are seen where a luminance ramp abuts the adjoining dark and light regions, respectively. Mach's proposal that the phenomenon derives from "reciprocal action", i.e. lateral inhibition, of neighboring areas within the retina, was later supported by direct neurophysiological recordings (Hartline and Ratliff 1965). Mach bands are robust over a

wide range of luminance gradients, persist under focal scrutiny, and have measurable apparent width and amplitude, which can be related to the size of corresponding center-surround receptive fields in the retina (Ratliff 1965).

The Hermann grid illusion has been attributed to lateral inhibition, and specifically to center-surround receptive fields (Baumgartner 1960). The illusory spots seen at the grid intersections are consistent with the expected size of retinal center-surround receptive fields (Ratliff 1965; Spillman 1977). It should be noted that while the effect is likely due to lateral inhibition, it is doubtful that it arises solely from circular-symmetric retinal receptive fields; orientation-selective units have been also been implicated (Levine et al 1980; Oehler and Spillman 1981; Wolfe 1984).

Several independent results would suggest that the lateral inhibition-induced features, if present, would be at least 6 arc min wide. Tyler (1973) showed that there is an upper limit of about 5 cyc/deg in the detection of sinusoidal variations in depth in stereograms, which is equivalent to a half-cycle of 6 arc min. Mitchison and McKee (1987) report depth averaging for dots separated by less than about 6 arc min. Also, Westheimer and Levi (1987) demonstrate a transition between attraction and repulsion in depth for targets separated by about 4-6 arc min. The attraction and repulsion effect is not particularly subtle: the magnitude of the apparent depth purturbation can be on the order of a minute of arc. Thus, if the spatial processes underlying these various lateral inhibition effects were to induce depth analogues to the corresponding binocular Hermann grid or Mach band stimuli, they should occur at approximately this scale and magnitude, or larger parafoveally.

In the depth version of the Hermann grid, consisting of a grid of squares above a background plane, the analogous effect would be illusory depth variations in the background at the grid intersections (either bumps or dips, depending on the disparity of the squares relative to the background grid). But the stereo analogue does not produce apparent illusory depth distortions at the grid intersections (Julesz 1965). Figure 5 shows a

representative stereo depth version of the Hermann grid. The background surface appears uniformly planar, both where fixated and parafoveally.

< figure 5 about here >

Figure 6 shows the stereo analogue to the ramp-like luminance profile that generates the traditional Mach bands in brightness. The stereogram consists of a linear disparity gradient flanked by regions of uniform disparity. The depth analogue to a Mach band would be line-like ridges and troughs in depth where the disparity ramp abuts the negative- and positive-disparity regions, respectively.

< figure 6 about here >

In examining for depth Mach bands, we used both dot and short-line stimuli with densities similar to that in figure 6, and primarily varied the slope of the linear ramp region with disparity gradients that ranged from 1:8 to 1:3. For the moderately shallow 1:8 disparity gradient, the disparity varied over a total of 10 arc min across the length of the ramp. The spacing between adjacent dots or short lines was varied over a range of 2.3 arc min to 6.1 arc min with increments of about 0.8 arc min. Also, because of the known anisotropy between horizontal and vertical configurations (Tyler 1973; Wallach and Bacon 1976; Rogers and Graham 1983) both orientations were used for each spacing. No Mach band-like depth effects were observed in stimuli where the ramp met the flanking level regions at a sharp crease, at any slope or orientation of stimulus. However, when the disparity profile was subtly modified to mimic Mach bands by the addition of slight ridges and troughs (0.8 arc min amplitude) at the margins between the ramp and the flanking regions, observers could readily discern the mock Mach bands.

A brightness effect similar to the Mach band is also to be found in a staircase luminance profile (e.g. figure 4a). In the immediate vicinity of each stairstep the brightness profile appears curved, an effect attributed to lateral inhibition (Ratliff 1965; Cornsweet 1970). The analogous depth effect would cause the uniform-disparity rectangles to appear *curved* as well as slanted in depth. But while the rectangles do appear slanted (figure 4b),

they appear distinctly planar. The disparity contrast across the step edge does not induce a local purturbation to the apparent surface in the vicinity of the edge.

While subtle depth effects analogous to Mach bands and the Herman Grid effect might eventually be demonstrated, we find it noteworthy that the analogous lateral inhibition effects are not readily apparent, particulary given that discrete stereo features have been shown to exhibit substantial depth attraction and repulsion when brought into close proximity. This discrepancy suggests two possibilities, presuming the absence of the analogous effects is valid. Recall that Laplacian-like filtering enhances luminance changes and facilitates their subsequent localization, and that Laplacian-like filtering can be achieved by lateral-inhibition or center-surround antagonism. One possibility, then, is that while some binocular mechanisms incorporate spatial lateral inhibition, those mechanisms are not involved in the detection of disparity change (i.e. depth edges). Alternatively, lateral inhibition artifacts might be induced in depth by center-surround disparity-summating mechanisms but later suppressed at a subsequent stage of surface perception. These alternatives are discussed further below.

4 General Discussion

The main points of the analogy between stereo depth and brightness contrast are *i)* both brightness and depth appear to be reconstructions from boundary contrast features and *ii)* both luminance and disparity contrast features are seemingly defined by discontinuities or second spatial differences. The first point is supported by a range of contrast effects which establish the dependence of depth, like brightness, on the available boundary conditions, several of which were shown above. The second point is supported by many studies that both demonstrate the lack of direct correspondence between depth and disparity, and relative insensitivity to constant disparity gradients. But the analogy has limits: while the reconstructions appear to embody similar computational principles, the detection of the

underlying contrast or discontinuity events in the two domains is probably achieved by different methods. We first review the case regarding depth reconstruction.

4.1 Depth reconstruction

The notion that stereo depth is reconstructed indirectly from disparity contrast, much as is brightness from luminance contrast, is not particularly intuitive. The optical geometry of the two images has been shown by many theoretical analyses to support the direct pointwise computation of spatial information such as depth, slant and absolute distance, provided that the necessary optical parameters are known from either retinal or extraretinal sources (Foley 1980; Mayhew and Longuet-Higgins 1982; Prazdny 1983). For simple binocular arrangements, often a pair of lines, it has been shown that the perceptions of depth, relative distance and absolute distance are all rather accurately predicted by the direct geometric relationships, with systematic errors that can be attributed to misperception of the actual angle of convergence, differential magnification in the two eyes, and so forth (see review in Foley 1980). Moreover, the optical geometry suggests that apparent depth should vary linearly with disparity but with the square of the observation distance. This effect, called depth constancy, is particularly apparent for small disparities and near observation distances (Ono and Comerford 1977; Ritter 1979; Wallach, Gillam and Cardillo 1979). It had been assumed, more or less tacitly, that such results would also apply to a continuous binocular surface, e.g. with apparent depth varying according to the disparity at each surface point., apparent surface slant varying according to the disparity gradient, and so forth.

Despite the elegance of the geometric equations and their predictions under certain controlled experimental circumstances, other observations argue against a direct depth computation. As mentioned earlier, apparent depth remains invariant over differing retinal motions in the two eyes, which suggests that depth derives from the relative arrangement of

disparities, and not their absolute retinal coordinates (Steinman & Collewijn 1980; Lappin, 1985). Furthermore, the particular spatial arrangement of binocular features also matters, as demonstrated by depth attraction or repulsion between adjacent features and the diminished depth from coplanar arrangements of binocular features (McKee 1983; Gillam, Flagg and Finlay 1984; Mitchison and Westheimer 1983; Stevens and Brookes 1988). These observations together suggest an indirect relationship between disparity and depth for disparity distributions associated with continuous surfaces. Rogers (1986), noting that second spatial derivatives of disparity are invariant over changes in viewing distance, has proposed that surface curvature features provide the basis for phenomenal depth constancy. In general, depth across continuous surfaces seems to derives *indirectly* from surface curvature features, which correspond to places where the second spatial differences of disparity are nonzero (Stevens and Brookes 1987, 1988), or in other words, where a gradient of relative disparities exists (Gillam, et al. 1988), which corresponds to differences of first differences (Mitchison and Westheimer 1984).

Thus the rather direct relationship between depth and disparity, demonstrated for isolated 3D features, does not apply to the depth across continuous surfaces. In particular, when disparity varies linearly, as would occur in viewing a continuous slanted plane, apparent depth is determined by the disparity contrast across the borders of the plane relative to the background, if available. In the absence of border disparity contrast, the slant of the plane in depth is dominated by the monocular interpretation (Stevens and Brookes 1988).

In the luminance domain, brightness contrast effects reflect limitations in the visual system's ability to reconstruct a luminance-related signal from measures of luminance change, presumably by interpolation (e.g. by lateral facilitation) within regions bounded by contrast features (Gerrits and Vendrick 1970; Davidson and Whiteside 1971; Arend 1973; Frisby 1979; Arend and Goldstein 1987). The stereo analogues suggest that binocular depth is likewise reconstructed, i.e. interpolated within regions bounded by disparity

contrast features. While the exact nature of the disparity features is not well understood, depth is elicited most effectively where the second spatial differences of disparity are nonzero, which correspond to surface discontinuity and curvature features (Stevens and Brookes 1987, 1988). And just as constant luminance gradients are effectively featureless and difficult to perceive, constant disparity gradients are similarly devoid of surface features and their interpretation in depth depends largely on the availability of disparity contrast, e.g. along their borders (Gillam et al. 1984; Stevens and Brookes 1987; Gillam et al. 1988; Stevens and Brookes 1988).

4.2 Discontinuity detection, spatial differentiation and lateral inhibition

The important binocular disparity features vis-a-vis surface reconstruction appear to correspond to loci where the second spatial differences of disparity are nonzero. Such features would be detected by measuring second spatial derivatives of disparity. Spatial differentiation can be achieved effectively by center-surround lateral inhibition operators, a strategy that seems general to sensory processing. While in the luminance domain the differentiation appears to be achieved by a circular-symmetric Laplacian-like filter, the known orientation anisotropy in sensitivity to disparity change would suggest against a circular-symmetric operator for the corresponding detection of disparity features. Instead, one might postulate directional derivative operators composed of elongated receptive fields with lateral inhibition between adjacent subfields.

As discussed, there is evidence for the existence of very short range (several arc minute) spatial lateral facilitation and inhibition in stereopsis. The effective spatial MTF of sensitivity to stereo depth also suggests lateral inhibition. But when one examines the stereo analogous to the traditional Mach band stimuli and the Hermann grid, the expected lateral inhibition effects are not readily apparent. We see three alternative explanations.

First, the lateral inhibition effects in depth may simply be more subtle than our explorations allowed for, or were masked by the experimental design. But if the measured MTF for stereopsis is taken as an indication of the size of the underlying receptive fields, and if these receptive fields are presumed to spatially summate disparities in the conventional lateral-inhibitory manner, their effects would presumably not be particularly subtle.

The second alternative is suggested by the conventional wisdom that relative, if not absolute, binocular disparities are available after binocular fusion. Differentiation-like filtering of their spatial distribution would serve to detect possible surface features (discontinuities and other curvature events). As in luminance processing, the differentiation operator would produce patterns of activity that could be misinterpreted (e.g. Mach bands). But unlike luminance processing, which has only limited access to the original luminance signal, disparity processing could independently determine from the disparities in the immediate vicinity of each possible feature true features from artifacts. We see no way to test this alternative given the current state of understanding, nor to distinguish this from the following alternative.

The third alternative is that disparity-contrast features (edges and other curvature-related surface properties) are detected by processes that do not induce the characteristic lateral inhibition effects reported by others. While both luminance contrast and disparity contrast features seemingly require localizing changes in gradient (i.e. non-zero second spatial differences), they are unlikely detected by analogous operators. It would be disadvantageous to perform spatial differentiation by disparity-sensitive receptive fields which, by analogy, summate all disparity signals within small neighborhoods. To do so would be to blur not only in the two spatial dimensions of the image, but in depth as well. This would pose problems for the perception of transparent surfaces, where in a given visual direction at least two surfaces planes of disparities might be expected. It would be preferable to perceptually segregate distinct those disparity signals likely associated with

separate surfaces, prior to attempting to detecting surface features. This alternative expects that those disparity distributions consistent with coherent surfaces (e.g. as measured in terms of local autocorrelation of disparity or local coplanarity) are treated differently than incoherent, or volume-filling, distributions (see evidence in Brookes & Stevens, 1989).

We should note that an alternative method for computing a (directional) second difference is to perform two consecutive first-differences. The initial first-difference operation might be a consequence of compensating for uncontrolled disjunctive and conjunctive eye movements by shifting or remapping images (Anderson and Van Essen 1987). As a result, positional information would be known only relatively (within each monocular image and between left and right images). The loss of absolute position information, analogous to the loss of absolute luminance information, causes simultaneous contrast effects in motion perception as well as stereopsis to (Loomis & Nakayama 1973; Rogers 1986; Bowns and Braddick 1986).

If another first-difference operation were performed on the remapped images, the result would approximate a second directional derivative of the (motion or disparity) fields. Spatial differentiation might therefore be achieved by shifting rather than convolution by lateral-inhibition operators. There are, however, substantial control issues, such as determining the scale or locality over which a given shift is performed, and in spatially delimiting the application of a given shift.

Remapping or shifting is a particularly elegant solution to the problem of compensating for a spatially-uniform error of unknown magnitude, where the relative signal is more reliable than the absolute. Anderson and Van Essen (1987) expect the shifter to be controlled by a combination of feedforward (e.g. direct estimation of the local signal to nullify) and feedback (e.g. minimizing residual error or maximizing measure of registration) strategies. Furthermore, if the magnitude and direction of the shift were determined locally for sufficiently small regions, the effect would be removing or reducing constant gradients as well as spatially uniform terms. Local remapping would thus account

for insensitivity to low spatial frequency disparity changes, as characteristic of differentiation operators. But it would also induce the depth artifacts in the vicinity of disparity discontinuities that are also characteristic of differentiation. Furthermore, the choice of control strategy is particularly difficult for small populations of binocular features, such described in (Mitchison and Westheimer 1984, figure 5). While remapping may contribute to the removal of low spatial frequency disparity information, it appears that the distribution of relative disparities is explicitly analyzed for planarity, as part of the extraction of surface discontinuity and curvature information.

In summary, stereo depth and brightness are analogous in that both are reconstructions. Just as apparent brightness is dominated by the distribution of contrasts, stereo depth is dominated by the distribution of disparity contrasts. The analogy does not extend, however, to the corresponding contrast-detection mechanisms.

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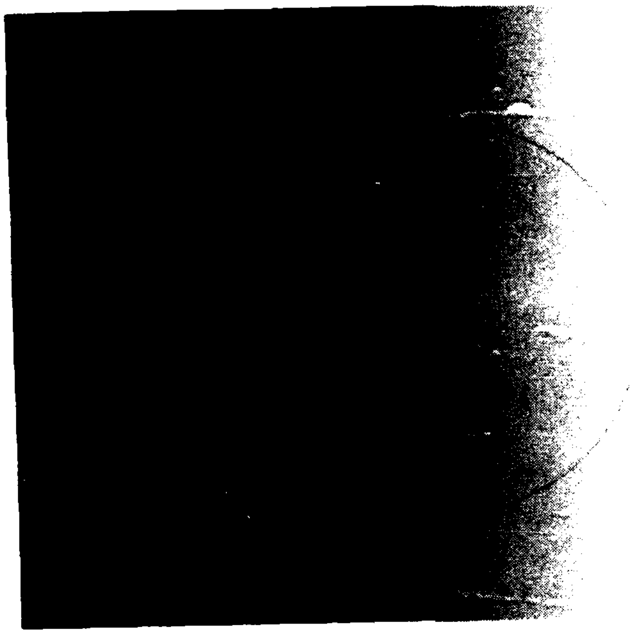
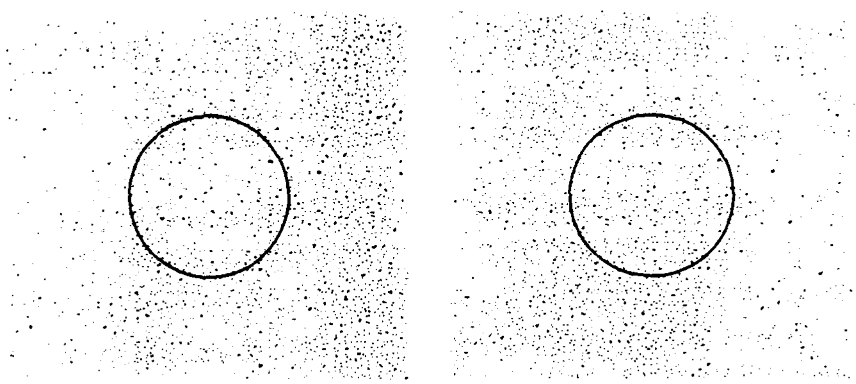
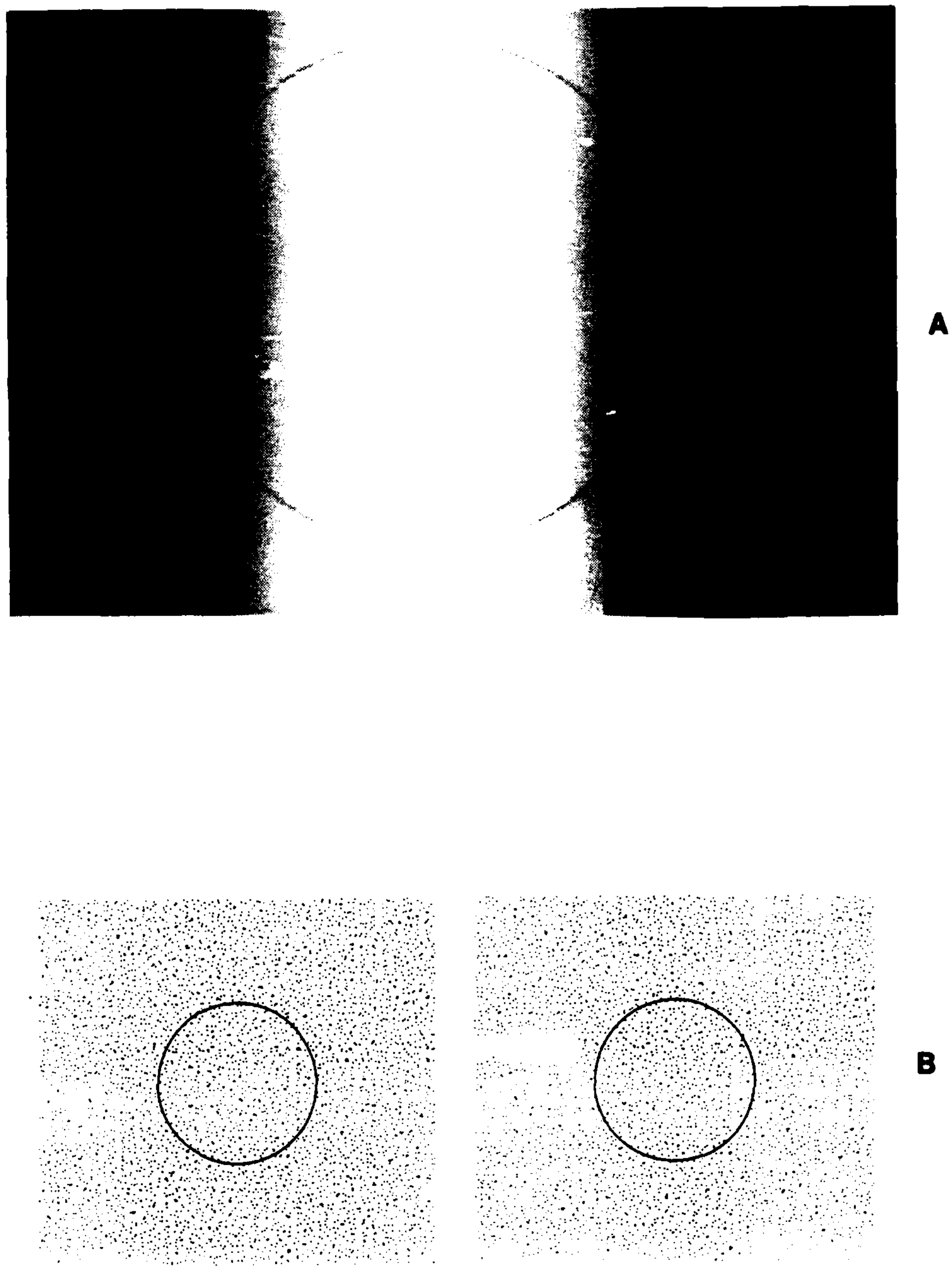


A

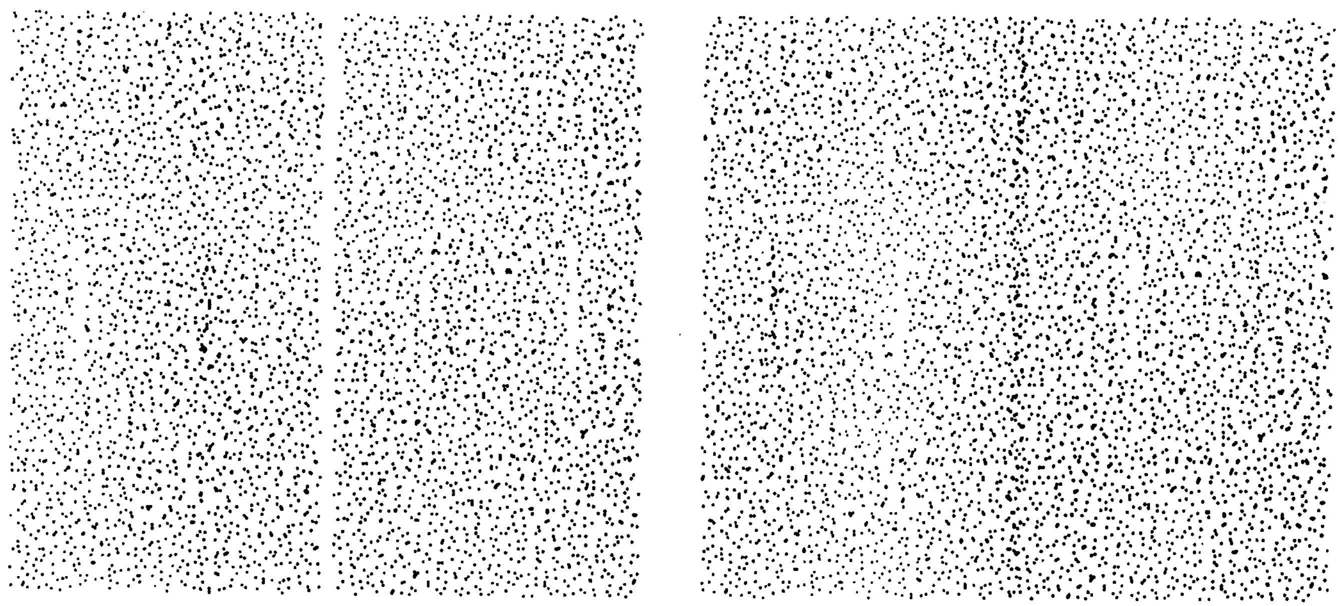


B

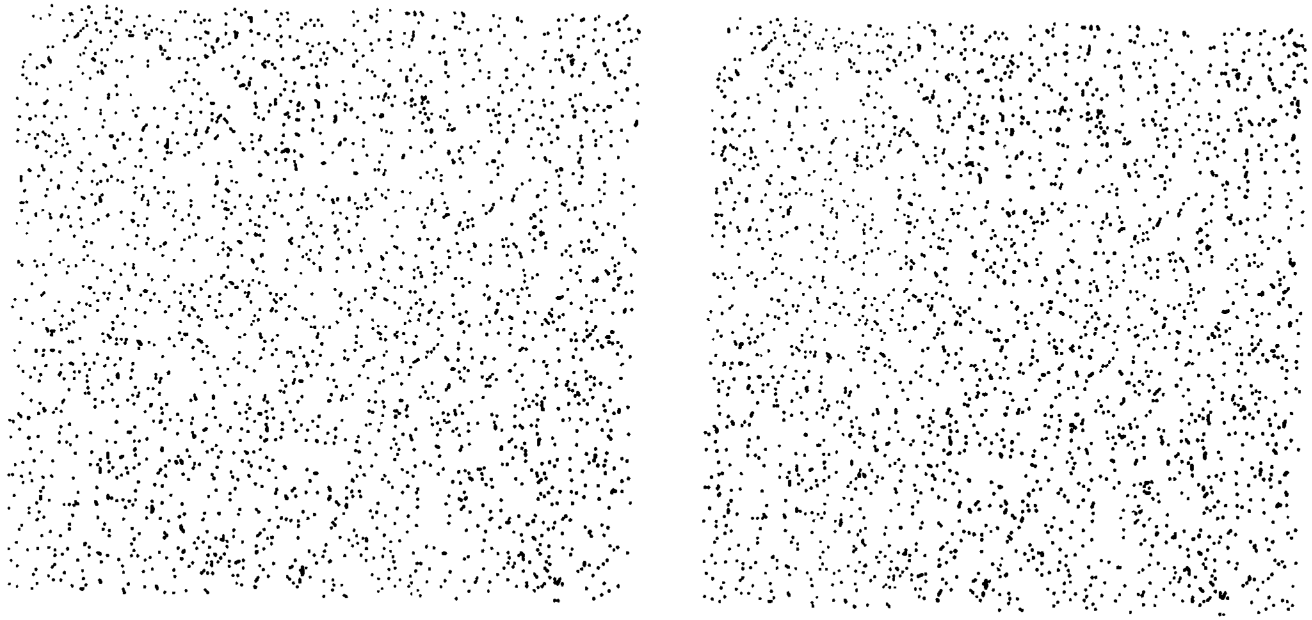
1. A variant of the Koffka ring. In *a* a constant luminance ring is embedded in a uniform luminance gradient background. In *b* the stereo disparity analogue presents a constant disparity ring against a uniform disparity gradient background. Note that the ring appears slanted.



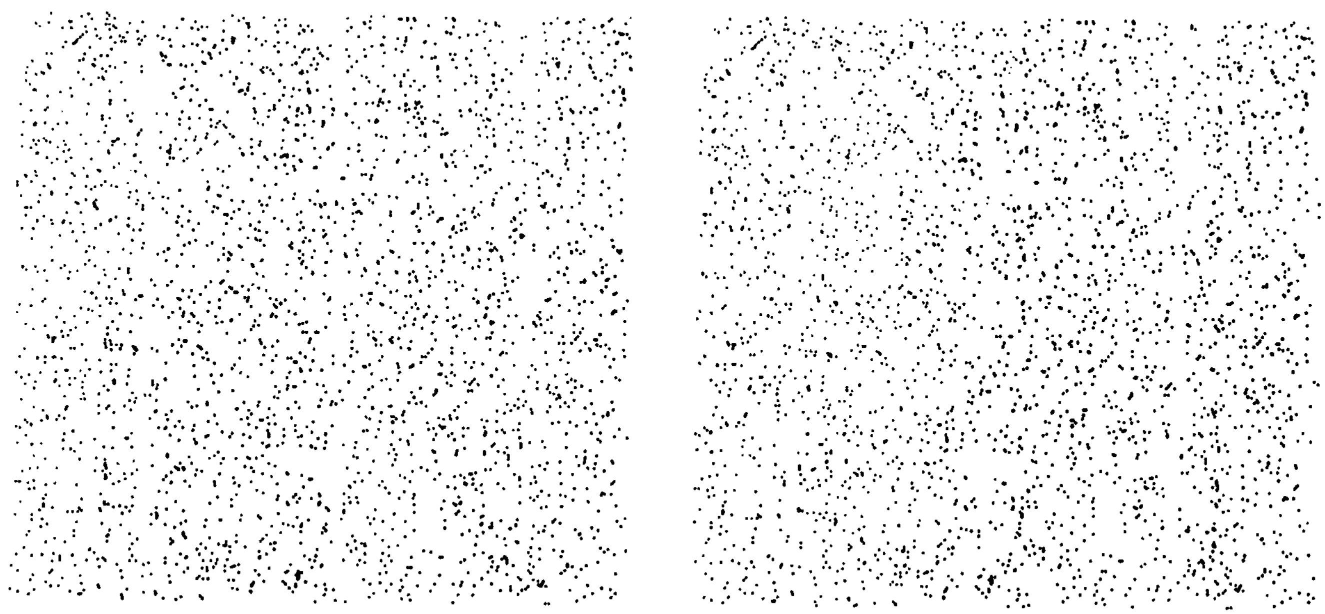
2. Similar to figure 1 but with a background with Gaussian profile. In a manner analogous to the variable brightness seen in the constant-luminance ring in *a*, the constant-disparity ring in *b* appears curved in depth.



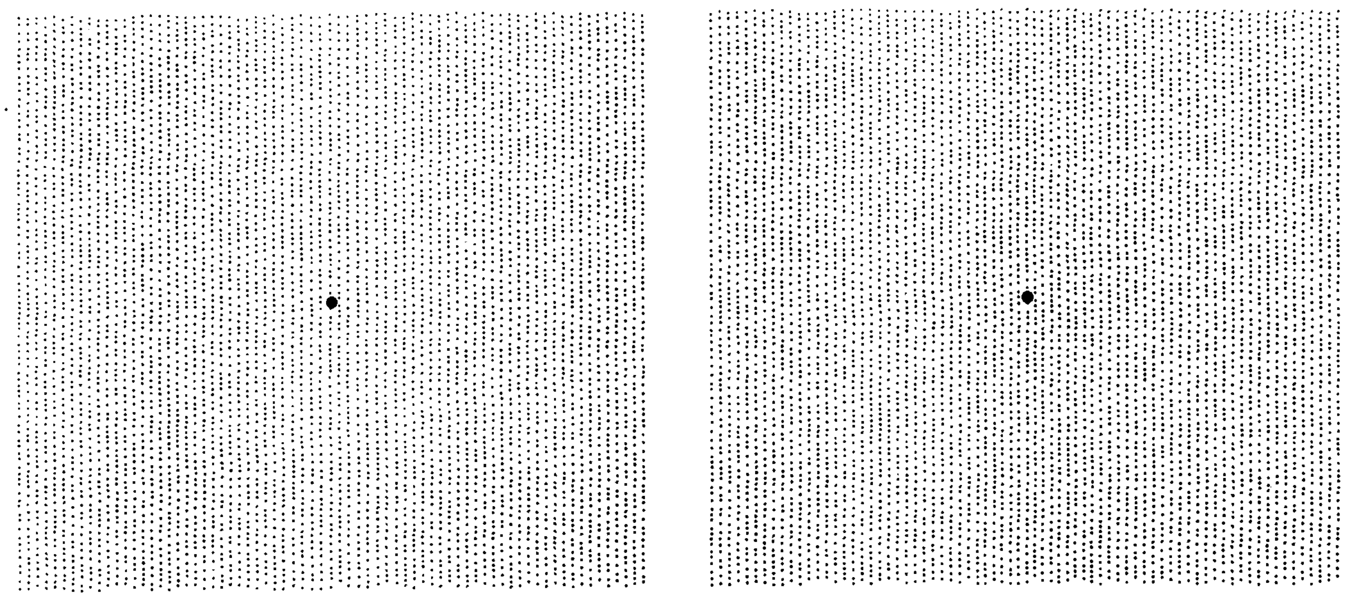
3. Stereo analogue to the brightness contrast effect. In this case there is no analogous effect.



4. Stereo analogue to the simultaneous contrast effect. The stairsteps appear slanted but planar.



5. Stereo analogue to the Hermann Grid.



6. Ramp in depth between two unslanted planes. The corresponding lightness version induces Mach bands at the discontinuities where the gradient changes. In the stereo case there is no analogue to the Mach bands.